

Upper Ocean Dynamics and Horizontal Variability in Low Winds

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Grant Number: N00014-05-10090

<http://www.whoi.edu/science/AOPE/dept/CBLAST/low/cblastlow.html>

LONG-TERM GOALS

Our long-range scientific objective is to observe and understand the temporal and spatial variability of the upper ocean, to identify the processes that determine that variability, and to examine its predictability. Air-sea interaction is of particular interest, but attention is also paid to the coupling of the sub-thermocline ocean to the mixed layer and to both the open ocean and littoral regimes. We seek to do this over a wide range of environmental conditions with the intent of improving our understanding of upper ocean dynamics and of the physical processes that determine the vertical and horizontal structure of the upper ocean.

OBJECTIVES

Little work has been done to explore air-sea interaction and upper ocean dynamics in very light winds, and few observations are available that describe the mesoscale and smaller scale horizontal variability of the upper ocean in such conditions. The objectives of this work are to observe and understand in low wind conditions:

- (1) how and why the vertical structure and properties of the surface boundary layer of the ocean (roughly the upper 20 to 50 m) evolve in time
- (2) how and why this evolution varies at horizontal lags of 10s of meters to 10s of kilometers on time scales of minutes to months.

To do so we seek to observe and identify:

- (1) the processes that spatially modulate the vertical structure of the upper ocean (including the depth, salinity, temperature, and velocity of the mixed layer),
- (2) the processes at work at the base of the mixed layer (such as entrainment),
- (3) the air-sea exchanges (fluxes of heat, freshwater, and momentum) that couple the boundary layers on horizontal scales of tens of meters up to 100 km.

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 30 SEP 2005		2. REPORT TYPE		3. DATES COVERED 00-00-2005 to 00-00-2005	
4. TITLE AND SUBTITLE Upper Ocean Dynamics and Horizontal Variability in Low Winds				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Woods Hole Oceanographic Institution, Clark 204a MS 29, Woods Hole, MA, 02543				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES code 1 only					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 13	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

APPROACH

The CBLAST-LOW (Coupled Boundary Layers Air-Sea Transfers – Low wind) collaborative research program was set up to address the need to better understand and predict the coupled boundary layers in low wind conditions. It combined observations (in situ and remotely sensed) at a site south of Martha's Vineyard, modeling, and simulations. Observational campaigns were carried out in the summers of 2001, 2002, and 2003. The site was selected because winds are often from offshore (from the south to southwest) with very large fetch while at the same time the synoptic variability yields a wide range of summer heating conditions. The air-sea interaction tower (ASIT) of the Martha's Vineyard Coastal Observatory (MVCO) is situated there approximately 4 km south of the island in 19 m of water. The major cooperative field effort, the Intensive Operating Period or IOP, was completed in August 2003. We participated in the field campaigns and are working collaboratively now on analysis of the observations.

WORK COMPLETED

Initial data processing and quality control has been completed (Pritchard *et al.*, 2002; Hutto *et al.*, 2003; Hutto *et al.*, 2005). Early results were presented at the 2004 Ocean Sciences meeting and the American Meteorological Society Air-Sea Interaction meeting in August 2004. The principal investigators met at the Ocean Sciences 2004 meeting and laid groundwork for collaborations and joint analyses and publication.

In 2001 we tested methods to observe the vertical structure of temperature, $T(z)$, of salinity, $S(z)$, of horizontal velocity, $U(z)$, with high temporal resolutions and vertical resolutions down to 0.5 m at a number of points separated by several m to 10's of km, observed the surface forcing and examined how it varies horizontally in the CBLAST-LOW domain, and obtained CTD profiles and sections to aid in initialization of regional ocean models (Pritchard *et al.*, 2002). Surface moorings were deployed at the 40 km and 20 km upwind sites (Fig 1a) and left in until mid-August, collecting month-long records of the surface forcing and temporal evolution of the vertical structure of the ocean. For a week, we set and instrumented a 3-D array; twenty vertical strings of instruments were attached to the 3-D array with instruments from the surface down to 25 m, and a Doppler profiler was hung from the center of the net. We also deployed a long-line 2-D array 1 km in length perpendicular to the shoreline. After 3 days we recovered the long-line array. After 5 days we recovered the 3-D array. During that week, 135 CTD profiles were collected, including two sections from the tower site to 40 km offshore and one section parallel to the shore. Shipboard sampling was coordinated with flights of the LongEZ aircraft, instrumented by C. Zappa (LDEO) and A. Jessup (UW) for infrared imaging of SST (Zappa and Jessup, 2005). The 6 bottom-mounted temperature, pressure, salinity instruments with recovered in mid-August with the surface moorings. CTD and moored observations were provided to Wilkin to support his regional ocean model development.

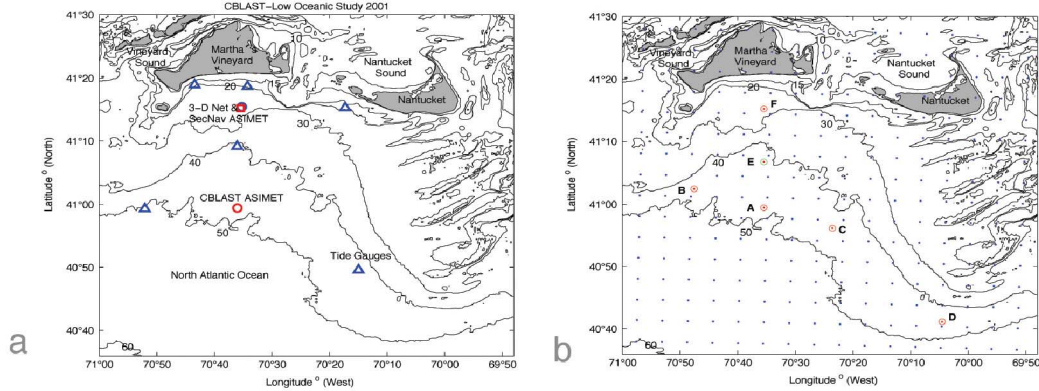


Figure 1. a) Locations of where the 3-D array, the two surface moorings (SecNav ASIMET and CBLAST ASIMET), and the six tide gauges (blue triangles) were deployed in 2001. b) Locations of the six surface moorings (A, B, C, D, E, F) deployed in 2002.

Apparent from the work in the summer of 2001 were the important roles of synoptic weather systems and regional oceanographic variability in setting the regional spatial context and of the energetic tidal currents and thermocline displacements that varied significantly both across and along isobaths in the region south of Martha's Vineyard. To better understand and document this variability and to concurrently examine the ability of regional atmospheric and ocean models to simulate this variability (and thus provide great support for the analysis of the observations), we deployed a six-mooring regional array (Fig. 1b) from late June to early September 2002. Data return from these moorings was high, and data have been made available to the modelers.

During the August 2003 Intensive Operating Period (IOP) surface meteorological and upper ocean measurements were collected from five heavily instrumented moorings, ten “light moorings”, five drifting buoys with precision, fast-response thermistor chains, and the *F/V Nobska*. *F/V Nobska* was instrumented to provide both direct and bulk flux estimates and also with a towed chain with fast response temperature or temperature/salinity sensors at 0.5 m vertical spacing. The mooring locations are shown in Figure 2a; Figure 2b shows the drifter and tow tracks.

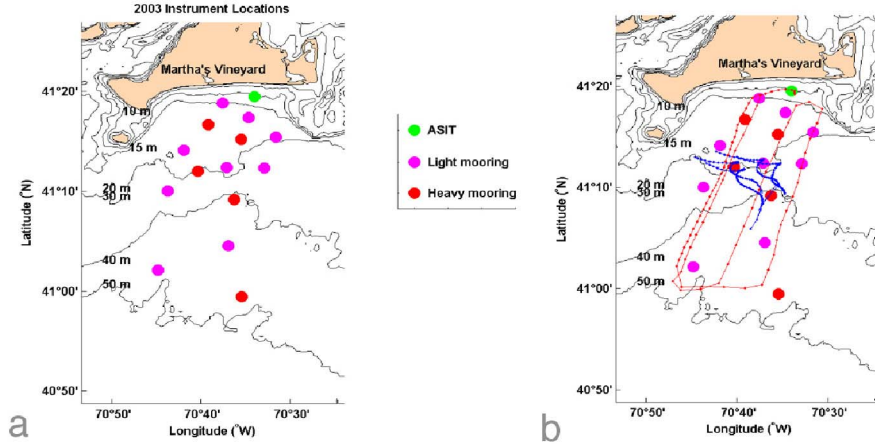


Figure 2. a) The locations of the 5 heavy surface moorings, 10 light moorings deployed in 2003 along with the location of the Air-Sea Interaction. b) Example tracks (blue) from one deployment of the drifting thermistor strings deployed during the IOP and of one deployment of the towed chain by FV Nobska (red) during the IOP to illustrate the additional sampling done over a wide range of spatial scales.

RESULTS

Data quality and return met or exceeded expectations. Technical reports have been written for the 2001 pilot experiment (Pritchard *et al.*, 2002), for the 2002 mooring deployments (Hutto *et al.*, 2003), and for the 2003 fieldwork (Hutto *et al.*, 2005). Data from the 2001 pilot revealed the presence of energetic solitons south of Martha's Vineyard (Pritchard and Weller, 2002, 2004, 2005). Results based on analyses of our data have been presented at the 2004 AGU Ocean Sciences Meeting (Weller *et al.*, 2004; Farrar *et al.*, 2004a; Pritchard and Weller, 2004), the 2004 AMS Boundary Layers and Turbulence Conference (Farrar *et al.*, 2004b; Wang *et al.*, 2004), and the 2004 International Geoscience and Remote Sensing Symposium (Thompson *et al.*, 2004).

At the beginning of CBLAST-LOW we anticipated that physical processes found in very shallow mixed layers that are not included in models like PWP (Price-Weller-Pinkel, Price *et al.*, 1986) could be important. To gauge the comparability of PWP to other 1-D models we re-examined the COARE data using other 1-D models, including Mellor-Yamada (Mellor and Yamada, 1982), KPP (Large *et al.*, 1994), and a simple diffusion based one-dimensional model. We examined data from the 3-D array and the two moorings deployed in 2001 for evidence of processes not explicit in such models and found that, in particular, we had captured strong high-frequency variability of solitons (Pritchard and Weller, 2005). These solitons had SST signatures, detected in coincident airborne infrared imagery (Zappa and Jessup, 2004). The 2002 data set has been used by CBLAST-LOW oceanic and atmospheric modelers to assess the ability of the models to replicate the observations (Wilkin and Lanerolle, 2004; Wang *et al.* 2004).

Data quality and return in 2003 were excellent, and a wide variety of conditions were sampled, including low-to-moderate wind conditions and the passage of atmospheric and oceanic fronts through the study region. Figure 3 shows one day of surface wind, net heat flux, air temperature, and 1 m

ocean temperature from a mooring near the center of the array, with warming of the upper ocean evident as the wind speed drops to close to 1 m s^{-1} .

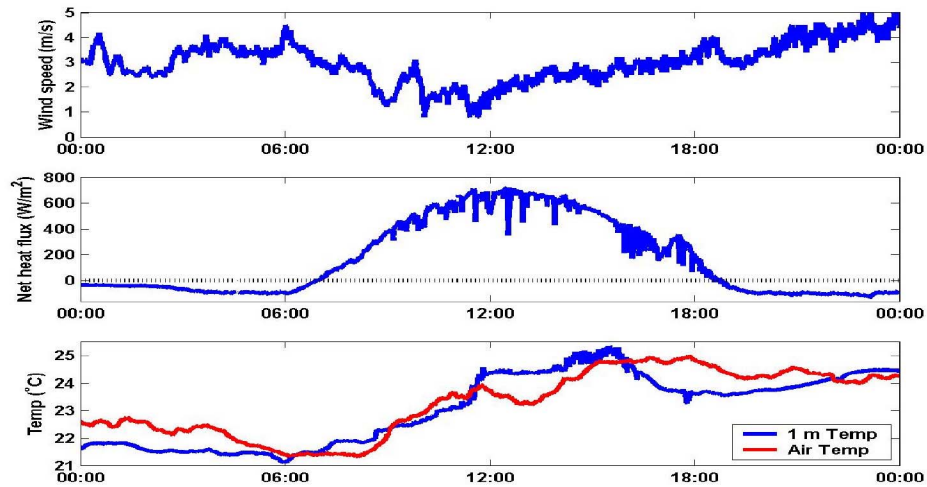


Figure 3. Surface wind speed (top), net heat flux (middle) and air and 1 m ocean temperatures (bottom) on August 15, 2003 (local time) from a mooring near the center of the array.

We have had three foci in recent work

- 1) improved understanding of the processes responsible for increased SST variability under low winds,
- 2) characterization of the evolution and variability of the coupled boundary layers in a range of conditions,
- 3) assessments of the predictive skill of regional models of the ocean and atmosphere (ROMS and COAMPS) combined with collaborative work addressed at identifying and improving shortcomings in the models.

Work to date in each of these areas of progress will be addressed briefly below.

Motivated by the strong spatial variability of SST observed under low winds at scales of 100 m to 10 km in the TOGA COARE program, specially designed measurement techniques were employed during CBLAST-LOW to sample this variability with adequate horizontal, vertical, and temporal resolution. Figure 4 shows an example of the spatial variability of SST observed on the afternoon of Aug 15, 2003, the day of low wind as shown in Figure 3. Quasi-periodic spatial variability in SST up to several tenths of a $^{\circ}\text{C}$ can be clearly seen in the spatially band-passed SST at a scale of about 1 km. Variability at larger and smaller spatial scales is also present, but it is not clearly visible in the band-passed data in Figure 4. On August 15, 2003 winds were low-to-moderate throughout the day, with wind speeds of $2.5\text{--}4.5 \text{ m s}^{-1}$ in the early morning hours decreasing to speeds of $1\text{--}2 \text{ m s}^{-1}$ by about noon local time. We carried out nearly overlapping ship transects, one around 7:30 and another around 16:30 (local time). The mean wind speeds and surface turbulent heat fluxes were nearly identical during the two transects, but the low winds and strong daytime heating led to the development of very strong, shallow temperature stratification, with a temperature gradient of about 2°C over the upper 2 m.

This strong temperature gradient and the thickness of this “warm layer” are roughly consistent with the scaling analysis of Price *et al.*, 1986. During the afternoon survey, the Cessna Skymaster flew almost directly over the *FV Nobska* along a similar track (Figure 4). The shipboard infrared SST measurements indicated that the 10-2000 m SST variability was much larger during the afternoon survey. Analysis provides direct evidence that the 100-2000 m SST variability observed under low winds is associated with oceanic internal waves. Figure 5 shows the temperature anomaly, relative to the 150 m along-track smoothed temperature, collected from the *FV Nobska* on Aug 15, 2003. Data from both the towed instrument chain and the shipboard radiometers are included, and the measurements at nine depths in the upper 5 m of the ocean show that there is a strong vertical coherence of horizontal temperature fluctuations extending from depth to the sea surface. The analysis indicates that these spatial fluctuations in SST are associated with oceanic internal waves, which cause temperature fluctuations extending from depth to very near the surface because of the relatively strong stratification that exists throughout the water column under low wind conditions (Farrar *et al.*, 2004a).

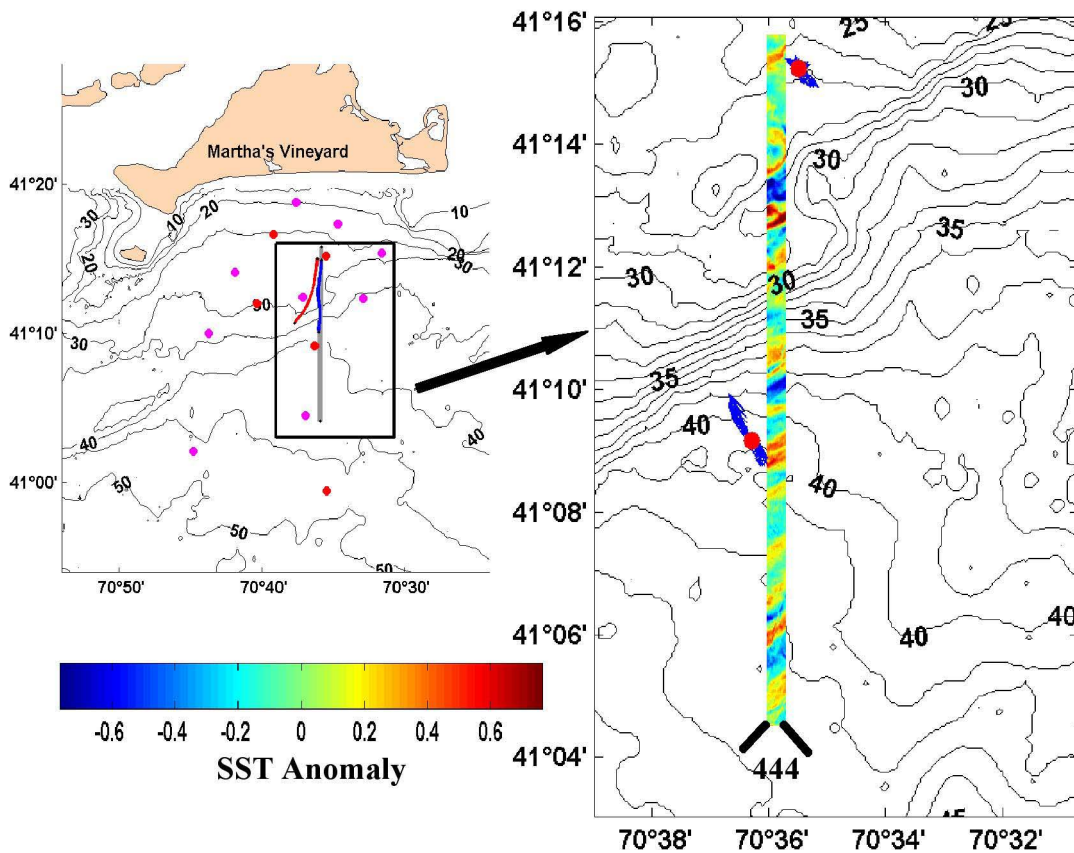


Figure 4: Left panel: Diagram showing the 2003 mooring array, the morning ship transect (blue line), the afternoon ship transect (red line), and the aircraft track (grey line) from August 15, 2003. Red dots indicate heavy moorings and pink dots indicate light moorings. Right panel: SST anomaly ($^{\circ}\text{C}$, colored) relative to 2.3 km along-track, smoothed SST and the current vectors (blue arrows) associated with 30 min. period internal waves at two nearby heavy moorings during the hour centered around the aircraft overpass. The internal wave crests are expected to be oriented perpendicular to the axis of the wave velocity fluctuations.

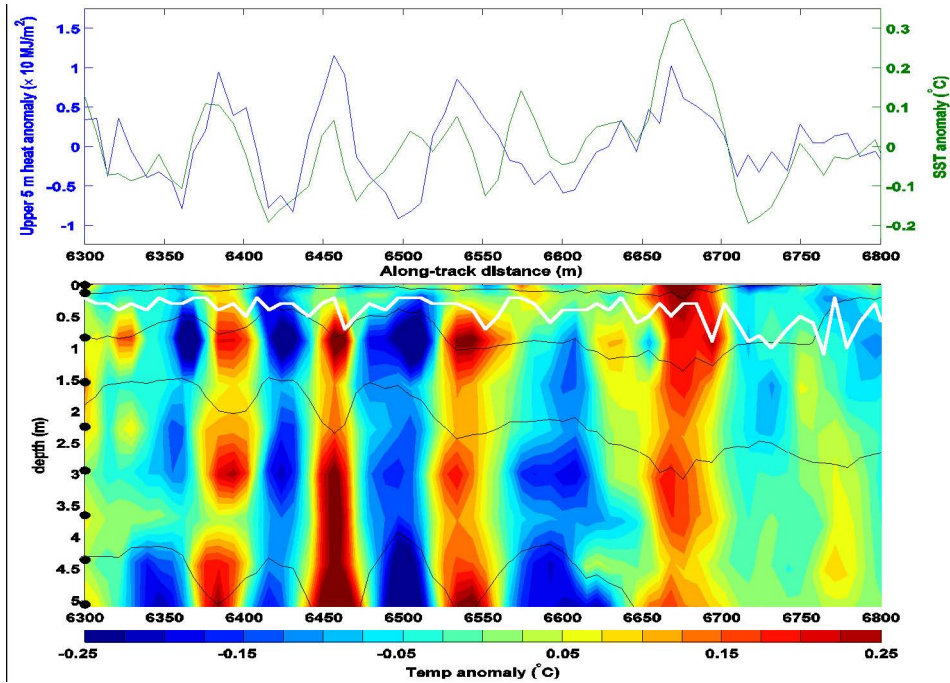


Figure 5: Surface (green, upper panel) and subsurface temperature anomaly (lower panel) and upper 5 m heat content anomaly (upper panel, blue line) relative to the 150 m along-track smoothed values. The measurement depths are indicated by black dots on the left side of the figure, and isotherms (black lines) are marked at intervals of 1°C. The white line marks the depth where the temperature is 1°C less than the surface temperature.

Preliminary analysis has allowed identification of some periods when the ocean responded strongly to atmospheric forcing, as well as periods when the atmosphere responded strongly to oceanic forcing. For example, Figure 6 shows that as the ship crossed SST variability associated with a cool intrusion from the east, there was spatial modulation of sensible and latent surface heat fluxes and of atmospheric temperature as observed by the Pelican aircraft. There is a very strong spatial modulation of the surface heat flux at the southern edge of the cold SST filament, with a combined change in latent and sensible heat flux of more than 150 W m^{-2} over a distance of about 5 km

Our data from the three summers includes time series at fixed points of surface meteorology, air-sea fluxes, and ocean variability; it also includes CTD sections and swaths of high resolution ocean sampling from the drifters and the towed chain. We have been working with S. Wang (NRL) to examine the success of COAMPS at predicting the surface meteorological and air-sea flux fields. With good air-sea flux fields, ocean models can be run to examine their realism. We have been working with J. Wilkin (Rutgers) to evaluate ROMS model runs. Initial efforts have focused on using the *in situ* oceanographic data from 2002 to evaluate ROMS model runs that are identical except for the vertical mixing parameterization employed (Wilkin and Lanerolle, 2004). The various mixing schemes lead to significantly different model simulations; of the three mixing schemes tested, the simulation using the KPP mixing scheme is the most realistic, particularly in simulation of SST and mean currents. We are working to examine if by focusing on sites within the CBLAST-LOW domain where the local heat balance is predominantly 1-D, we can isolate the 1-D dynamics and use

comparisons between the model and the observations to guide the selection of the 'best' parameterization for vertical mixing and thus improve predictions and hindcasts.

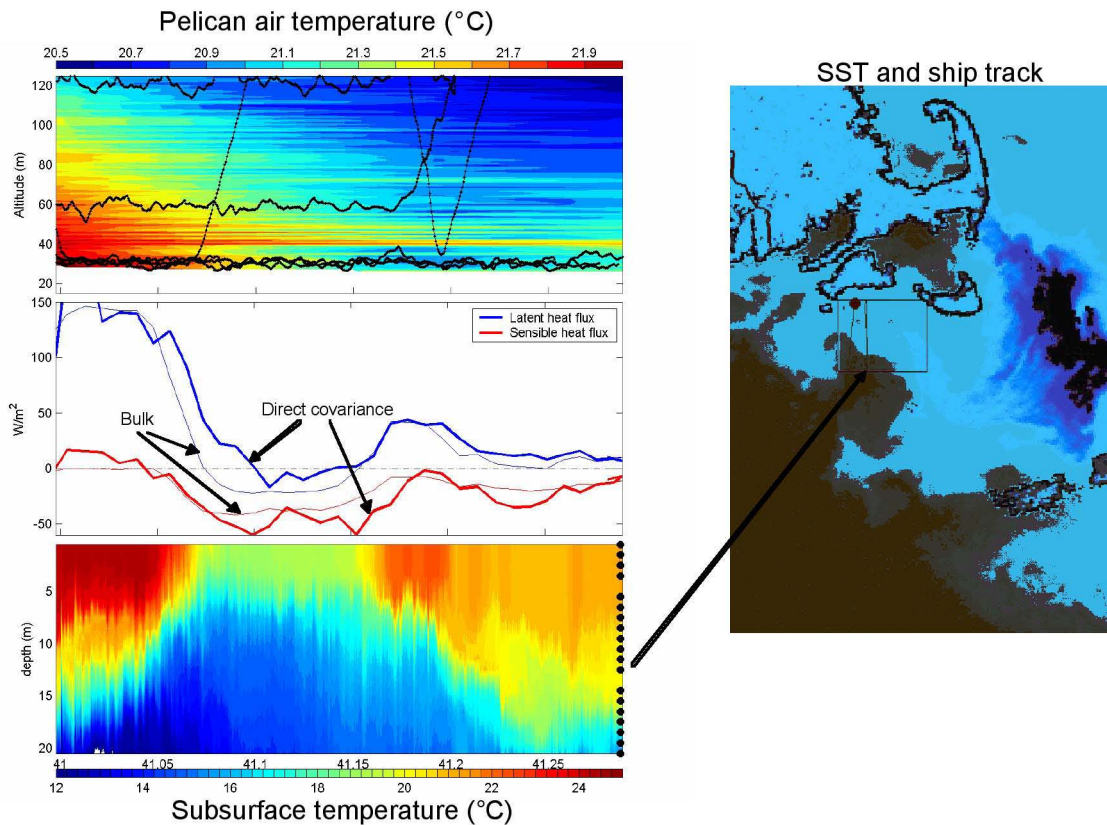


Figure 6. *On the left, subsurface thermal structure (lower), sensible and latent surface heat fluxes (middle), and atmospheric temperature from the Pelican aircraft (upper) associated with the ship track shown on the right executed on the afternoon of August 19, 2003.*

The spatial variability in SST and upper ocean temperatures is at times strong. The tow chain section from August 19 shown in Figure 6 is blown up in Figure 7 to show the presence of a gradient of 5°C in 4 km. The oceanic spatial variability and its link to either the surface forcing and/or ocean processes is the subject of continuing analysis.

IMPACT/APPLICATIONS

The observations of the surface meteorological and air-sea flux fields and of the structure and variability of the littoral ocean are unique. They provide the basis for determination of processes at work in governing the variability of the shallow, coastal ocean and lower atmosphere. They also provide a basis for testing the realism of atmospheric, ocean, and coupled models of the coastal region and for improving coastal predictions by developing, testing, and implementing model improvements.

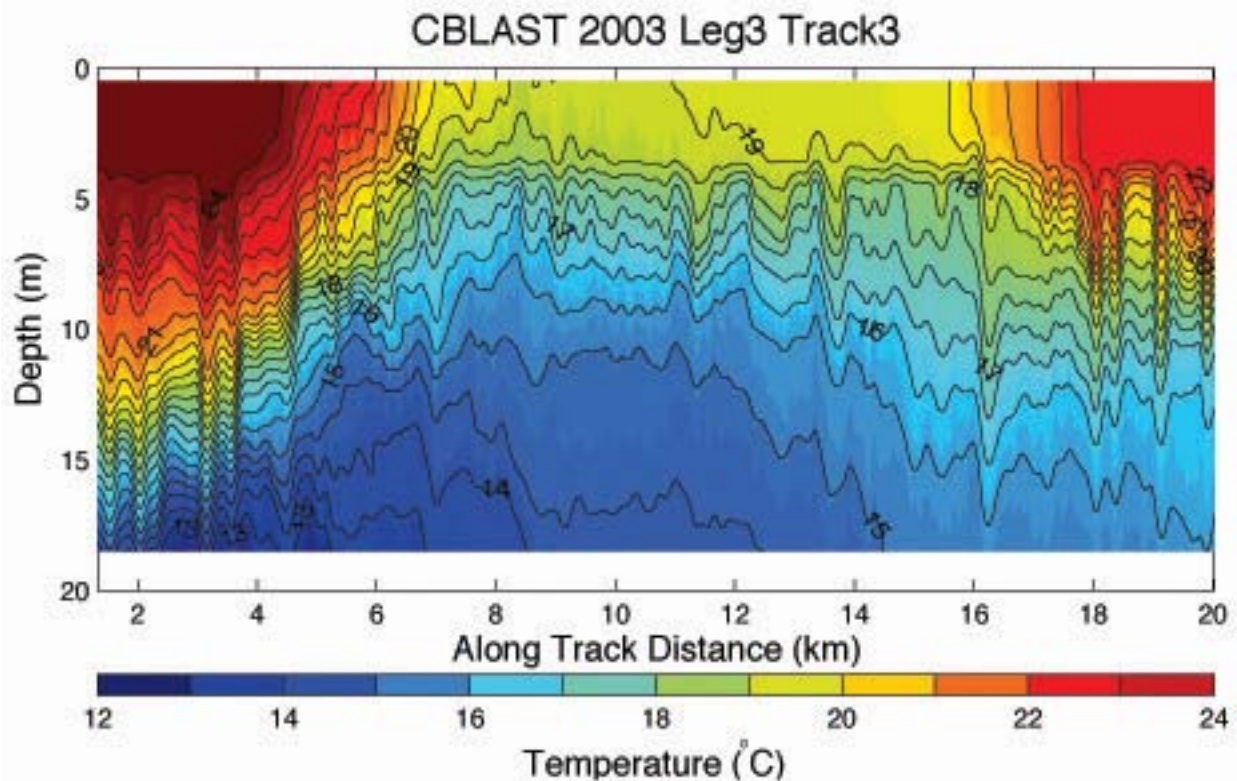


Figure 7. Contour plot of temperature data from a tow chain transect made from offshore to onshore on August 19, 2003. The temperatures in the upper 5 m show spatial gradients as large as 5°C over 4 km. A tongue or filament of water cooler than 19°C penetrated the CBLAST region; the water on either side was 22 to 24°C.

RELATED PROJECTS

This work is closely related to our studies of horizontal variability and predictability that were supported by a Secretary of the Navy/Chief of Naval Operations Chair. That work has focused on the impact of environmental variability on mine countermeasures activities in the shallow water. CBLAST-LOW, with its explicit sampling of the horizontal as well as vertical and temporal dimensions, has provided exceptional observations of the structure and variability of the littoral ocean. We are working closely with John Wilkin (Rutgers) to assess the success of his ocean model at realistic simulations of the CBLAST observations. We are also working closely with Chris Zappa (LDEO) and Andy Jessup (UW APL) on joint analyses of their aircraft observations of the ocean's surface together with our in-situ data.

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